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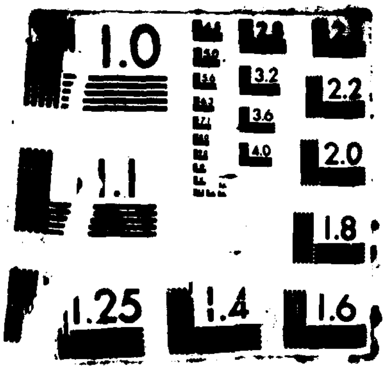
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# Atmospheric Icing of Transmission Lines

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# Atmospheric Icing of Transmission Lines

**Karen Henry**

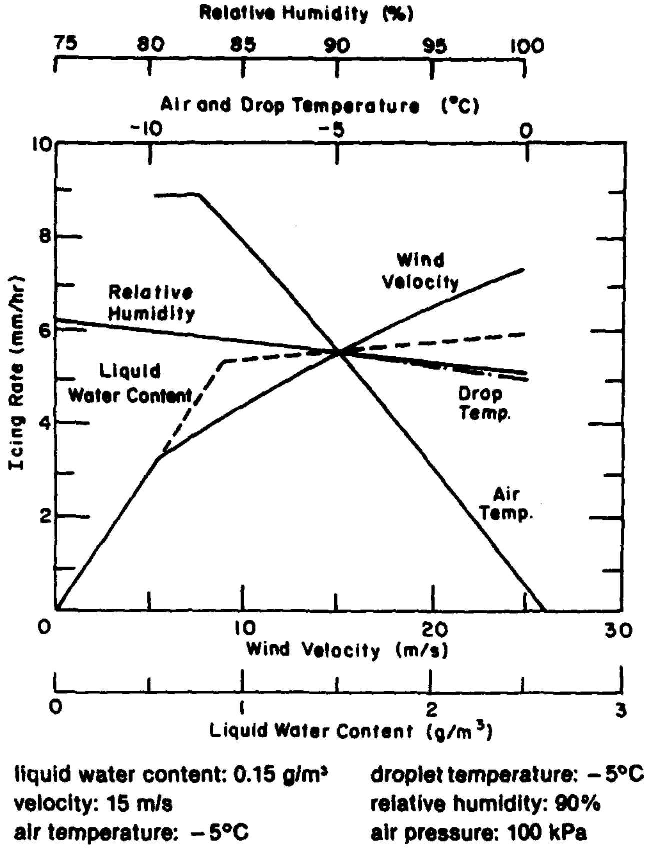
## Introduction

In recent years the damaging effect of atmospheric icing on transmission lines has become an increasingly important issue. As we become more dependent on reliable energy and communications, even in remote areas, transmission line failure is a costly inconvenience at the very least, and it can threaten human life. At the same time, it is desirable to minimize construction and maintenance costs. These circumstances have led to more research into the causes of atmospheric icing and its effects on transmission lines.

In the last several years significant progress has been made in our understanding of the problem. One of the most important developments has been an increased understanding of the combined effect of the wind and the shape of an ice accretion on the loads exerted on a conductor. Also, more is known about conditions under which line vibrations, or galloping, occur. Computer models can now estimate the effect of atmospheric conditions on icing.

This digest is intended primarily for the technical person who is unfamiliar with atmospheric icing on transmission lines. It is a synthesis of information from the *Proceedings of the First International Workshop on the Atmospheric Icing of Structures* (Minsk 1983), which features many presentations dealing with transmission line icing. Other references are also cited throughout the report.

*The author, a civil engineer, is a member of CRREL's Civil Engineering Research Branch.*

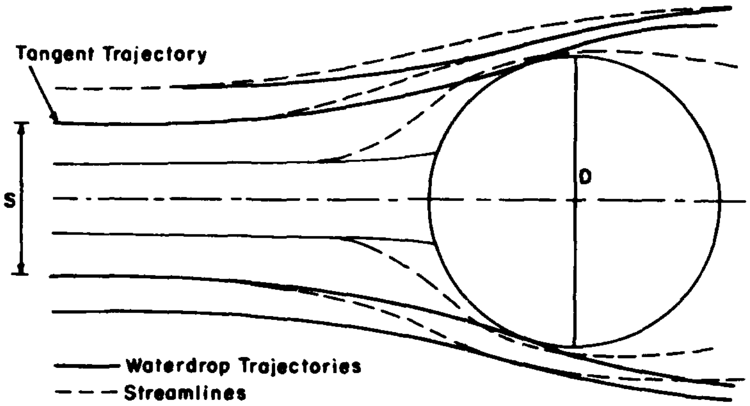



*1. Rate of icing at the stagnation point of a 0.3-m-diameter cylinder, showing the effect of varying each parameter independently. The stagnation point is the line on the cylinder where free-stream fluid is brought to rest (i.e. the centerline of the windward side of the cylinder). (After Stallabrass 1983.)*

## The physics of icing

Ice accretion occurs whenever supercooled water droplets strike and adhere to a surface that has a temperature of freezing or below. The amount and characteristics of accreted ice depend on the source of water particles, the environment and the interaction of the particles with the accreting surface.

Atmospheric icing is primarily controlled by four variables—air temperature, wind speed, liquid water content and droplet size. Liquid water content is defined as the mass of water per unit volume of air. Figure 1 shows how three of these parameters, as well as relative humidity and drop temperature (assumed to be equal to air temperature), affected the rate of icing in laboratory experiments (Stallabrass 1983). Because liquid water content and droplet size are not routinely measured by meteorologists, it has been difficult to accurately quantify the relationship between these variables and icing intensity in field situations; most work in this area focuses on wind tunnel experiments and modeling (Laforte et al. 1983).




*2. Collection efficiency of a cylinder. If the mass flux is constant, this can be represented linearly by* E = S/D. *(After Brown and Krishnasamy 1984, Stallabrass and Hearty 1967.)*

The interaction between the droplets and the object determines the mass of the droplets striking the wire. This interaction is quantified by the collection efficiency $E$, defined as the ratio of the mass flow of impinging water droplets to the mass flow of droplets that would have struck the surface if they had not been deflected by the air stream (Brown and Krishnasamy 1984). The collection efficiency varies between 0 and 1 and, assuming a constant mass flux, can be represented by the ratio of distances $S/D$ (Fig. 2). Brown and Krishnasamy (1984, Chapter 3) provide a summary of the theory and determination of the water droplet trajectories around a cylinder.

Since there is a considerable range of droplet sizes in the atmosphere at any given time and $E$ is different for each droplet size, $E$ is best represented by a weighted mean. Researchers have found that $E$ can be accurately estimated using a mean droplet size $E_m$ when the size of the droplets exceeds 20–30 $\mu$m (Ackley and Templeton 1979). When icing occurs on ridges and mountaintops ("in-cloud" icing), however, droplets are usually smaller than 20 $\mu$m, and some error is introduced by using $E_m$ (Brown and Krishnasamy 1984).

Ice that accumulates on structures in the atmosphere can be either glaze or rime, depending on the conditions of formation. Table 1 describes the appearance, density and conditions of formation of atmospheric ice types (Minsk 1980).

Glaze ice forms when the droplets do not freeze immediately upon impact but instead form a surface film of water, which then freezes. In glazing conditions the surface film of water is continuously present. Because of this, "runback" icing and icicle formation may occur during glazing. In runback icing the unfrozen water flows some distance over the

**Table 1. Types of ice from atmospheric sources (Minsk 1977).**

| *Type of ice* | *Appearance* | *Density (g/cm³)* | *Conditions of formation* |
|---|---|---|---|
| Glaze | A hard, well-bonded, generally clear homogeneous ice | 0.7–0.9 | Supercooled water droplets at a temperature close to freezing (0° to -3°C) and wind speeds of 1-20 m/s |
| Hard rime | A hard, granular, white or translucent ice growing in the direction of the wind | 0.1–0.6 | Supercooled water droplets at a temperature of -3° to -8°C, wind speeds generally 5-10 m/s |
| Soft rime | A white, opaque, granular ice with delicate structure only loosely bonded, growing in the direction of the wind | 0.01-0.08 | Supercooled water droplets at a temperature of -5° to -25°C and low wind speed (1-5 m/s) |

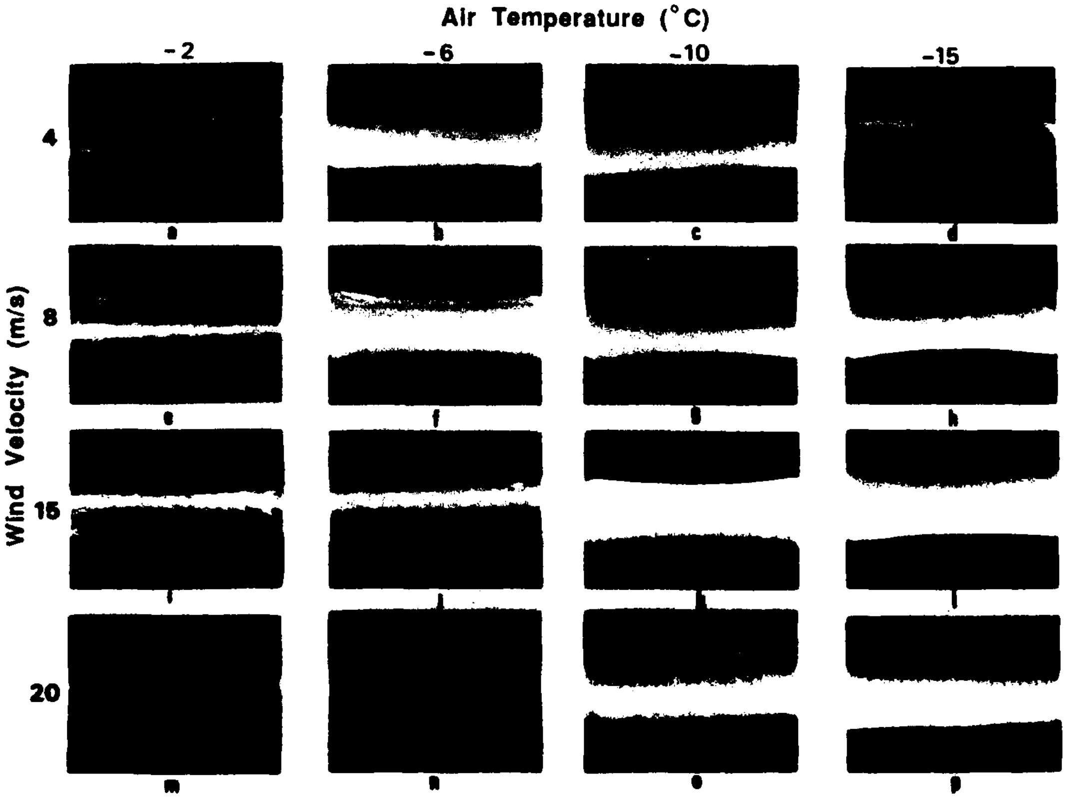
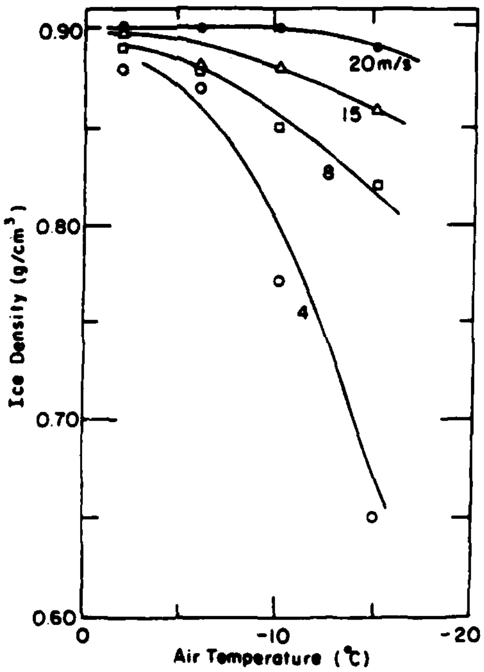
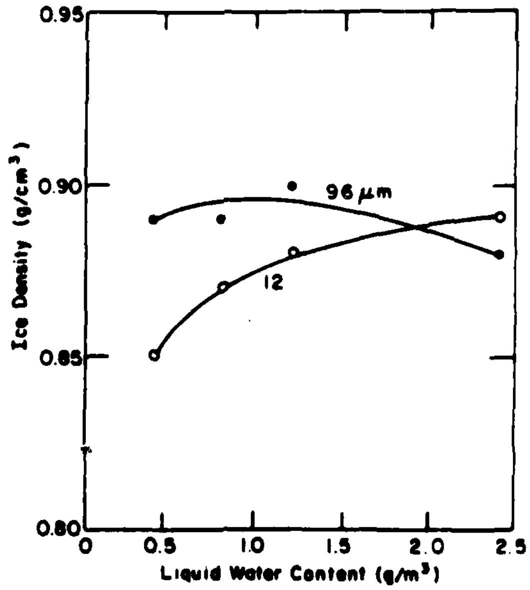



*Figure 3. Ice accretions grown under different ambient temperatures and air velocities. (From Laforte et al. 1983.)*




*a. Density of ice as a function of ambient temperature and air velocity. The droplet diameter is 38 μm and the liquid water content is 0.8 g/m³.*




*b. Density of ice as a function of droplet size and liquid water content. The ambient temperature is -6°C and the air velocity is 8 m/s.*

*4. Variables affecting ice density. (From Laforte et al. 1983.)*

**surface before freezing. Glaze ice is transparent, has a smooth surface, and is the densest form of atmospheric ice. Glaze ice on a conductor may be cylindrical, or it may have some sort of elliptical form with the long axis parallel to and on the leeward side of the wind.**

**Rime ice forms when water droplets freeze immediately on**

impact. It is opaque and less dense than glaze. Because the droplets freeze on impact, rime ice grows toward the wind. Rime ice can be subdivided into "soft rime" and "hard rime," terms that refer to the densities of the ice.

The boundaries between glaze, hard rime and soft rime are not abrupt but are gradual transitions. Some researchers also define "milky ice," a transitional form between hard rime and glaze in appearance and density (Govoni and Ackley 1983). Figure 3 demonstrates the influence of air temperature and wind velocity on the appearance of accreted ice grown in a wind tunnel. Air temperature, droplet size and liquid water content also affect the density of accreted ice (Fig. 4).

## Icing on wires

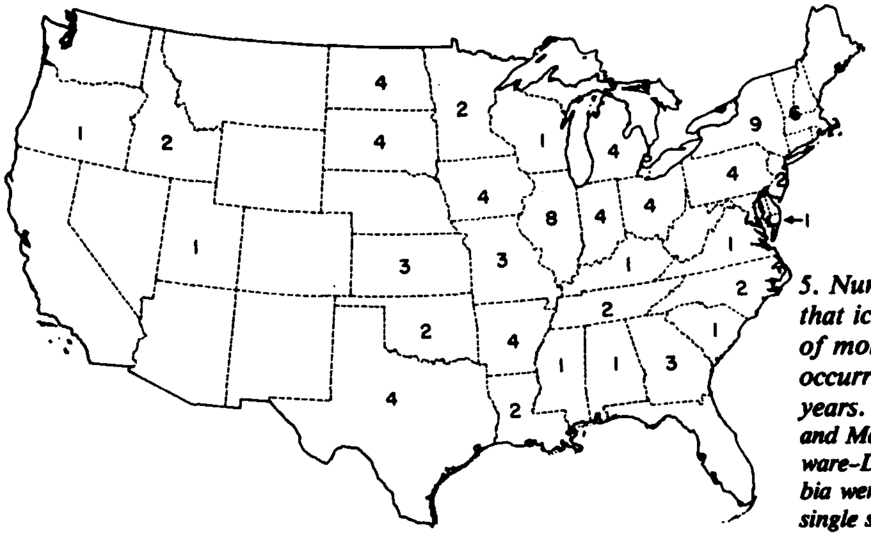
The main technical issues associated with icing on transmission lines are:

- Predicting the occurrence and accumulation rate of icing,
- Estimating the loads caused by ice and by the combined effects of ice and wind, and
- Mitigating these effects, especially transmission line galloping.

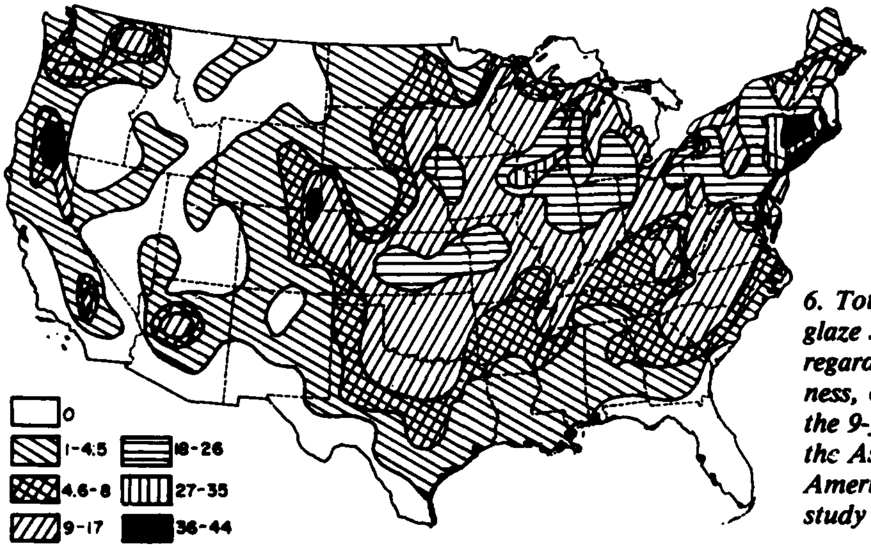
### *Predicting events and severity*

Design values for ice and combined ice and wind loads are difficult to determine because records of glaze and rime ice are not routinely kept. Figure 5 presents an estimate, by state, of the number of times that ice thicknesses greater than 2.5 cm occurred over 50 years. These values were often determined somewhat subjectively because of the lack of consistent records. Figure 6 represents the number of glaze storms during a 9-year study by the Association of American Railroads. There are no reliable data for rime icing or for accompanying wind loads; however, Tattleman and Gringorten (1973) indicated that maximum wind speeds usually exceed 10 m/s (22 mph) for most ice storms that deposit 2.5 cm or more of ice in the United States. A design aid that could be used for siting and designing communications and transmission lines is discussed by Raenskii and Prokhorenko (1977); "ice districting charts" have been developed for the U.S.S.R, classifying geographic regions according to the frequencies of dangerous deposits of glaze, rime, sleet and wet snow. No such charts are available for the United States or Canada.

There are a number of computer models being used to predict various aspects of icing, such as ice growth rate, total




*5. Number of times that ice thicknesses of more than 2.5 cm occurred during 50 years. (New England and Maryland-Delaware-District of Columbia were treated as single states.)*




*6. Total number of glaze storms, without regard to ice thickness, observed during the 9-year period of the Association of American Railroads study (Bennett 1959).*

volume of ice accumulated, ice loads, wind loads, shape of ice accretions, and cable twisting angles. Many of these models are based on theoretical assumptions that are yet to be verified or apply only to limited conditions or both.

Computer modeling of ice accretion is hampered by the lack of a large, high-quality, field data base. Field data are particularly sparse for liquid water content and droplet size, both of which can significantly influence the intensity of icing. In addition, meteorological data for some remote sites have never been gathered and must be extrapolated from distant meteorological stations. Table 2 is a list of computer models recently compiled by Brown and Krishnasamy (1984); the last two entries were added for this report.

**Table 2. Computer models of ice accretion. (After Brown and Krishnasamy 1984.)**

| *Model description* | *Input parameters* | *Accretion type* | *Model output* |
|---|---|---|---|
| **Imai (1953)**<br>Theoretical expressions for wet and dry growth accretion under in-cloud icing conditions | Wind speed<br>Air temperature<br>Cylinder radius<br>Droplet radius<br>Liquid water content | In-cloud icing (glaze or rime) | Growth rate of ice mass on conductor |
| **Leavengood (1972)**<br>Empirical (graphical) relationships of rime ice diameter as a function of mean wind speed and icing duration. Based on observed icing data from California, Japan and Germany. | Mean wind speed during storm<br>Storm duration | Rime icing | Total diameter of ice |
| **Borisenkov and Pchelko (1972)**<br>Energy heat balance expression for maximum icing intensity of a 1-cm² surface normal to a flow of freezing spray. Tables provided for deriving model input parameters. | Air temperature<br>Air pressure<br>Sea-surface temperature<br>Sea-surface salinity | Freezing spray icing (wet growth) | Ice accretion intensity (g/cm² h) on 1-cm² surface |
| **Kachurin et al. (1974)**<br>Energy balance expression for theoretical growth rate of freezing spray icing on cylinder. Theoretical results empirically related to observed ice accretion loads on Russian trawlers and expressed as nomogram. | Wind speed<br>Air temperature<br>Sea-surface temperature<br>Wave height<br>Sea-surface salinity | Freezing spray icing (wet or dry growth)<br>Information on ice density not given | Ice accretion rate on vessel (tons/hr) |
| **Chaine and Skeates (1974)***<br>Semi-empirical model for calculating radial ice accretion thickness on conductor from freezing precipitation. Uses climatological data. | Wind speed<br>Freezing precipitation rate<br>Conductor radius | Glaze | Horizontal, vertical and equivalent radial ice thickness from icing storm. Also computes ice and wind loadings during storm. |
| **Chaine (1974)**<br>In-cloud icing model based on the air frame icing prediction method of Jensen (1963). Determines ice thickness from precipitable water. Uses climatological data. | Surface and upper-air values of:<br>Air temperature<br>Relative humidity<br>Pressure | Glaze<br>Mixed rime<br>Rime | Ice thickness and density for a storm (accretion surface not defined). Model output intended as index of severity rather than accurate values. |
| **Meteorology Res., Inc. (1977)***<br>Theoretical model of ice accretion on cylinder incorporating calculation of collection efficiency and the heat balance of the icing surface. Model incorporates time-dependent feedback of changing conductor radius on collection efficiency and surface energy balance. Uses climatological data. | Wind speed<br>Precipitation intensity<br>Temperature<br>Pressure<br>Cloud liquid water content<br>Conductor diameter<br>Median droplet radius | Glaze<br>Rime<br>Hoar frost<br>Wet snow<br>(fixed densities for each type) | Ice thickness (radial) on conductor, ice load and wind loadings during storm. |
| **Cansdale and McNaughton (1977)**<br>Theoretical model of ice accretion on a non-rotating cylinder. They | | (Paper unobtainable) | |

* Indicates models that are most appropriate for estimating ice loads on conductors and towers.

**Table 2 (cont'd). Computer models of ice accretion. (After Brown and Krishnasamy 1984.)**

| *Model description* | *Input parameters* | *Accretion type* | *Model output* |
|---|---|---|---|
| consider accretion as a function of angle around cylinder and include runback water. Also consider possibility of mixed accretion icing (supercooled droplets and ice crystals). Designed for investigation of helicopter rotor blade icing. | | | |
| **Lozowski et al. (1979)*** | | | |
| Theoretical model of ice accretion on non-rotating cylinder for mixed accretion icing. Similar to Cansdale and McNaughton (1977). Developed for investigating helicopter rotor blade icing. Includes runback and shedding of liquid water. No time-dependent feedbacks. | Air temperature<br>Liquid water content<br>Ice crystal content (opt.)<br>Cylinder diameter<br>Wind speed<br>Cylinder roughness (smooth or rough)<br>Droplet radius distribution (hard coded) | Fixed ice density of 890 kg/m³ for wet (glaze) or dry (rime) accretion | Icing rate in 5° sectors from 0° to 90° around cylinder for one time step. |
| **Ackley and Templeton (1979)*** | | | |
| Time-dependent numerical model for ice accretion on cylinder. Does not include runback. | Air temperature<br>Liquid water content<br>Droplet radius (mean) or<br>Droplet radius distribution<br>Wind speed | Uses Macklin's (1962) ice density correlation for rime<br>Wet growth ice density set at 917 kg/m³ | Plotted profiles of ice thickness at each time step. Tabular output of energy fluxes and collection efficiency at each time step. |
| **Makkonen (1981)** | | | |
| Analytical expressions for determining ice accretion rate on stagnation line of cylinder. | Air temperature<br>Wind speed<br>Liquid water content<br>Droplet diameter<br>Cylinder radius | Rime<br>Glaze | Icing rate on stagnation line of cylinder. |
| **Ervik and Fikke (1982)*** | | | |
| Model using climatological data and observed ice accretion data as feedback to produce icing estimates for any location in Norway. Details of model not given in paper. | Surface and upper air meteorological data.<br>Analyzed and interpolated values of height, temperature, humidity & wind at 850-mb level. | Hard rime<br>Soft rime<br>Glaze<br>Hoar frost<br>Snow/sleet | Time series of ice loadings at arbitrary location/site for use in determining extreme value statistics. |
| **McComber (1982)*** | | | |
| Numerical simulation model of ice accretion on a cable taking into account cable rotation. Model uses finite element scheme which incorporates feedback of changing ice accretion shape on collection efficiency. | Wind speed<br>Droplet size distribution<br>Cable radius<br>Cable torsional rigidity<br>Liquid water content | Rime (dry growth only) | Shape of ice accreted on cable over specified time interval, cable twisting angle. |
| **Lozowski and Oleskiw (1983)*** | | | |
| Numerical simulation of time-dependent rime icing without runback on cylinder and airfoil. | Wind speed<br>Droplet size distribution<br>Cylinder radius<br>Liquid water content | Rime (dry accretion only) | Ice accretion shape on cylinder. |
| **Stallabrass (1979)** | | | |
| Energy balance expression for the theoretical icing rate of a cylinder | Air temperature<br>Sea-surface temperature | Freezing spray<br>Icing (wet or dry | Ice rate (kg/m² s) or growth rate of ice thick- |

* Indicates models that are most appropriate for estimating ice loads on conductors and towers.

**Table 2 (cont'd). Computer models of ice accretion. (After Brown and Krishnasamy 1984.)**

| *Model description* | *Input parameters* | *Accretion type* | *Model output* |
|---|---|---|---|
| exposed to freezing spray icing conditions. | Droplet diameter<br>Wave height<br>Wind speed | growth)<br>Ice density of 900 kg/m³ assumed | ness (mm/h) |
| **Goodwin et al. (1982)**<br>Expression for change in radius of conductor from freezing precipitation. | Total measured freezing precipitation<br>Wind speed<br>Droplet fall velocity<br>Ice density (value of 900 kg/m³ usually assumed). | Freezing precipitation icing. Assumes all freezing precipitation accretes as ice. | Change in conductor radius, i.e. radial ice thickness. |
| **Bain and Gayet (1982)**<br>Addition of variable ice density effects into the model of Lozowski et al. (1979). | Air temperature<br>Liquid water content<br>Droplet size distribution<br>Cylinder diameter<br>Wind speed<br>Cylinder roughness (smooth or rough scenarios)<br>Ice crystal content (opt.) | In-cloud icing (wet or dry growth)<br>Incorporates variable ice density expressions from Macklin (1962) | Shape of ice accretion on cylinder. Ice density versus angle around the cylinder. |
| **Makkonen (1984)***<br>Theretical model of in-cloud icing for stagnation line of cylinder. Includes time-dependent feedbacks from changing conductor diameter and variable ice density | Wind speed<br>Cylinder diameter<br>Droplet diameter<br>Air temperature<br>Liquid water content | In-cloud icing (wet or dry growth)<br>Uses Macklin's (1962) variable ice density formulation | Ice mass<br>Conductor diameter<br>Average ice accretion density |
| **MEP (1984)***<br>Theoretical model of ice accretion based on the MRI model. Uses expression given by Makkonen (1984) to calculate collection efficiency. Designed for use with hourly climatological data. | Wind speed<br>Cylinder diameter<br>Droplet diameter<br>Air temperature<br>Liquid water content<br>Precipitation rate | Glaze<br>Rime<br>Hoar frost<br>Wet snow<br>(Fixed densities for each type) | Radial ice thickness<br>Total ice load<br>Maximum transverse wind load |
| **Sakamoto (pers. comm.)**<br>Semi-empirical model for wet snow accretion on conductors. | Wind speed<br>Precipitation intensity<br>Wind direction<br>Conductor orientation<br>Mean air temp for storm<br>Mean wind speed for storm | Wet snow | Radial snow thickness<br>Snow load |
| **Egelhofer (1984)**<br>Time-dependent model to predict rime accretion on wire free to rotate. Finite element technique is used to obtain velocity field adjacent to wire. | Droplet size<br>Ambient temperature<br>Liquid water content<br>Wind speed<br>Wire size<br>Wire stiffness<br>Total model time | Rime | Ice thickness<br>Drag and lift forces<br>Total ice load |
| **McComber and Govoni (1985)**<br>Simple semi-empirical model based on ice load measurements taken at Mt. Washington, N.H. | Droplet size<br>Air temperature<br>Liquid water content<br>Wind speed | Rime<br>Glaze | Ice load variation as a function of time. |

* Indicates models that are most appropriate for estimating ice loads on conductors and towers.

In a study that used field data, McComber and Govoni (1985) reported that ice loads in steady icing conditions increase exponentially with time. In addition, they presented a theoretical basis for an exponential growth model. Their analysis was based on data from five icing events at one location, so caution should be exercised in generalizing from these results. This contribution is nonetheless a significant step in developing icing models and verifying them in the field.

*Predicting ice and wind loads*

Calculations for combined ice and wind loads do not account for ice accretion shape. In a series of wind-tunnel experiments, McComber et al. (1983) determined that the design criteria used by a hydroelectric power company to predict combined ice and wind loads (which assumed cylindrical glaze accretions) always underpredicted vertical and horizontal forces. This is attributed to two factors, the first being that asymmetrical ice accretions observed in the field (and the lab) offer more wind resistance, resulting in a negative lift force, which is equivalent to adding to the weight. The second factor is that the calculations of horizontal loads assume that the accretion is glaze ice; when less-dense rime forms, the volume is larger for the same weight of ice, so the drag force is larger. These results are significant because ice accretions on wires are usually asymmetrical because of the torsional ri-

**Table 3. Calculated and experimental ice-wind loads for tests conducted in a wind tunnel (McComber et al. 1983).**

| *Sample number* | *Calculated forces (N/m)* | | | *Measured forces (N/m)* | | | *Ratios* | | |
|---|---|---|---|---|---|---|---|---|---|
| | $F_H$ | $F_V$ | $F_T$ | $F'_H$ | $F'_V$ | $F'_T$ | $F'_H/F_H$ | $F'_V/F_V$ | $F'_T/F_T$ |
| **Wind speed 22.35 m/s (50 mph)** | | | | | | | | | |
| 2 | 20.1 | 45.4 | 49.7 | 67.2 | 65.6 | 93.9 | 2.99 | 1.44 | 1.89 |
| 4 | 20.3 | 45.8 | 50.1 | 39.6 | 84.6 | 92.9 | 1.95 | 1.83 | 1.85 |
| 8 | 26.0 | 65.7 | 70.7 | 54.3 | 67.1 | 86.3 | 2.09 | 1.02 | 1.22 |
| **Wind speed 26.37 m/s (59 mph)** | | | | | | | | | |
| 2 | 28.0 | 45.4 | 53.3 | 98.4 | 76.8 | 124.8 | 3.51 | 1.69 | 2.34 |
| 4 | 28.2 | 45.8 | 53.8 | 58.3 | 95.6 | 112.0 | 2.06 | 2.09 | 2.08 |
| 8 | 36.1 | 65.7 | 75.0 | 77.0 | 68.5 | 103.1 | 2.13 | 1.04 | 1.37 |

Note—The orientation of the experimental cable in the wind tunnel is not specifically stated, but it is assumed to be perpendicular to the wind direction. The subscripts $H$, $V$ and $T$ indicate horizontal, vertical and total forces, respectively. All the samples were soft rime.

gidity of the conductor. Table 3 contains the results of the wind tunnel experiments by McComber et al. (1983). More research and field measurements are required in order to present quantitative recommendations.

### *Mitigating icing effects*

Most research on mitigating icing effects centers on the galloping of transmission lines. Corrective measures and design procedures for reducing or withstanding icing loads are also being studied.

Galloping occurs on ice-coated conductors. It is a low-frequency, high-amplitude, wind-induced vibration associated with the effect of ice accretions on the aerodynamics of the conductor (Rawlins 1979). The most significant effect of galloping is flashover and the resulting power outages. Flashover happens when lines touch each other and electrical discharge occurs. Rawlins (1979) provides an excellent review of what is known about the causes and effects of galloping. In general, galloping requires an asymmetrical ice deposit (usually glaze or hard rime because these forms adhere well) and a moderate to strong wind at an angle greater than about 45° to the line.

Rawlins (1979) classified galloping countermeasures in three main categories:

- Removing or preventing ice formation,
- Interfering with galloping mechanisms to prevent galloping from building up, and
- Making lines tolerant of galloping.

Ice formation can sometimes be prevented, and accumulated ice melted, by heating conductors electrically (either by increasing the current or by attaching special transformers that will produce heat in low-temperature conditions) (Rawlins 1979). This technique may be difficult to use at high wind speeds due to the enormous amount of power required to overcome convective heat loss. There has been little success with the use of "ice-phobic" coatings in preventing ice build-up; most problems arise from the inability of the coating to adhere to a surface under adverse conditions.

Many utilities increase phase-to-phase and phase-to-ground clearances to prevent flashovers. Interphase ties are also used to enforce the phase separation and reduce the motion of the wires with respect to each other. Numerous damping devices are also employed, with varying degrees of success. Rawlins (1979) provides more specific information and more references on this topic.

Egelhofer (1984) developed a computer model that predicts the accretion of rime ice on a wire free to rotate; he found that "...from a design standpoint, a stiff wire with a short span between support structures or phase spaces is desirable... ." This is because the resulting icing rate is lower. However, the results need to be verified with field data, and the effect of this configuration on glaze accretions was not determined.

McComber and Govoni (1985) reported their observations of ice break-up during accretion in field tests conducted on Mt. Washington, New Hampshire. The ice broke near the ends of a stranded wire as a result of torsional vibrations (due to relatively high winds—20 m/s and greater). The result was that pieces of ice rotated independently while still adhering to the conductor, and ice continued to accrete at unacceptably high rates. (The broken ice did form more cylindrical accretions, however, which would cut down on the aerodynamic effects discussed earlier.)

It is thought that the use of flexible conducting wires in regions where icing is likely to occur is undesirable. The greater torsional vibrations probably lead to heavier ice build-ups, and the wires are also subject to greater vertical vibrations. According to Ackley,* wires that are neither fixed cylinders nor very flexible (that is, they rotate only slightly) probably have the best ability to shed rime ice, but the optimal stiffness is not yet known.

In summary, significant advances have been made recently in ice accretion modeling and in understanding combined ice and wind load effects. More high-quality field data are needed to test icing models, including more observations of glaze and rime ice with concurrent records of liquid water content and droplet size distribution. Statistical data on the occurrence and severity of ice storms on a regional basis are rare and would be a valuable planning and design tool. In addition, design modifications such as using relatively stiff conductor wires and decreasing span length are thought to be desirable, but more research is needed to quantify these recommendations.

* S.F. Ackley, personal communication, USA CRREL, 1986.

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